

SOFT BANGKOK CLAY STABILIZED WITH CEMENT AND BAGASSE ASH

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Abstract

The main objective of this study is to assess the effectiveness of bagasse ash (BA), a type of agricultural waste from the sugar industry, as an admixture to improve the unconfined compressive strength, chemical composition, and microstructural properties of soft clay. Ordinary Portland cement (OPC) type I is partially replaced by BA and mixed with soft clay to generate cement bagasse ash-admixed soft clay. The test results show that the replacement of OPC with BA can enhance the strength by as much as that of OPC alone, and 20% BA is considered the optimum. The correlation between the modulus of elasticity and the unconfined compressive strength can be expressed as a linear function. The strength development with curing time can be represented using an exponential function.

Keywords: Bagasse ash, soil improvement, unconfined compressive strength, water-to-binder

Introduction

The improvement of soft clay properties has been performed widely to mitigate problems in civil engineering projects that result from construction on top of soft clay deposits. It is well known that soft clay has a low shear strength and high compressibility. Chemical stabilization is used extensively in deep soil mixing techniques in which a cement-based

slurry is mixed with the existing soft clay (Jamsawang *et al.*, 2011). However, ordinary Portland cement (OPC) is expensive, resulting in higher construction costs. The feasibility of using cheap pozzolanic materials to replace OPC has been studied. Pozzolanic materials are SiO_2 - and Al_2O_3 -based materials that react with the calcium hydroxide generated by

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hydrating cement to form additional cementitious materials that, in themselves, generate little to no cementing functionality. Industrial waste is increasingly being considered as a soil stabilizer. By-products such as sludge and bottom ash have been observed and found to be useful as pozzolanic materials for the improvement of the properties of fine-grained soils (Güllü, 2014).

Bagasse ash (BA) is one of the main by-products from bagasse combustion in the sugar cane industry. In Thailand, most of the BA is deposited in landfills. Landfill demand is rapidly becoming an environmental burden (Somna *et al.*, 2012). The application of sugar cane BA in concrete production provides an acceptable solution to some of the environmental concerns. BA can be used as a mineral admixture mainly due to its high content of SiO_2 . Many researchers have reported that BA exhibits satisfactory behavior as a blended cementitious material in concrete and has great potential for use in other applications (Alavéz-Ramírez *et al.*, 2012). BA can be ground to obtain fine particles and then added to concrete to produce high-strength concrete. The use of 10-30% BA in concrete (by dry weight) was observed to increase the concrete strength and decrease the concrete porosity and resistance to chloride penetration because the fineness of BA contributes to a finer pore structure, which reduces chloride permeation and diffusion (Rukzon and Chindaprasirt, 2012). The addition of 10% BA increased the compressive strength of cement paste at all hydration ages (Singh *et al.*, 2000). The replacement of cement with 20% BA by dry weight was the optimum, and the strength of the soil increased with the curing time. The main advantage of using BA is that it reduces chloride diffusion by more than 50% without negatively affecting the other properties of the hardened concrete (Amin, 2011). In summary, the most common pozzolanic materials used for the improvement of the engineering properties of soft clay are OPC, lime, fly ash, bottom ash, and industrial waste.

Therefore, in this study, cementitious composites used BA as a partial replacement for OPC in the stabilized soft clay. Then, the main objectives of the study were to determine

the compressive strength and the effect of the water-to-binder (W/B) ratio and to propose the optimum ratio of the BA replacement based on compressive strength tests, X-ray diffraction (XRD), and scanning electron microscopy (SEM).

Materials and Methods

Materials

Three kinds of materials used in this research were soft clay, cement, and BA. The soft clay used in this study was typical soft Bangkok clay that was excavated from the site of a condominium building project near the Chaophraya River in Nonthaburi Province, Thailand. Soil samples were collected at depths of 3 to 8 m from the original ground level. The physical properties of the soft clay are summarized in Table 1. The OPC used in this study was type I with a specific gravity that is 3.15 and the fineness of the OPC is $2,900 \text{ cm}^2/\text{g}$. The BA employed in this study was sampled from a sugar production factory in Singburi Province, Thailand. The BA was produced by being burned at a temperature of approximately 600 to 800°C to generate electricity. The specific gravity of the BA was 2.35, and the fineness of the BA ranged from 2,800 to $3,000 \text{ cm}^2/\text{g}$ after grinding for 30 min. The chemical compositions (% by dry weight) of the soft clay and BA compared with that of the OPC according to X-ray fluorescence (XRF) spectrometry are presented in Table 2. The BA contains 71.63% silicon dioxide (SiO_2), 9.37% aluminum oxide (Al_2O_3), 5.1% ferric oxide (Fe_2O_3), and 5.9% calcium oxide (CaO). The sum of the SiO_2 , Al_2O_3 , and Fe_2O_3 is

Table 1. Properties of tested soils

Property	Value
Natural moisture content, w_n (%)	80.6
Specific gravity, G_s	2.68
Initial void ratio, e_0	2.16
Wet unit weight (kN/m^3)	15.18
Undrained shear strength (kPa)	14.5
Liquid limit, w_L (%)	78.49
Plastic limit, w_P (%)	34.30
Plasticity index, PI (%)	44.19
Unified soil classification	CH

Table 2. Chemical composition of soft clay, OPC, and BA

Compound	Soft Clay	OPC	BA
SiO ₂	62.5	16.3	71.63
Al ₂ O ₃	18.4	3.72	9.37
Fe ₂ O ₃	8.49	3.55	5.10
CaO	1.07	69.5	5.90
MgO	2.35	0.728	1.67
SO ₃	1.86	5.04	0.70
K ₂ O	2.96	0.37	2.50
Other	2.37	0.792	3.13

86.1% which is more than 70% of the total composition, so that it can be classified as Class N pozzolan material according to ASTM C618 (ASTM International, 2000). The mineralogical compositions of the soft clay, OPC, and BA were determined using XRD (Figure 1(a-b) and 1(c), respectively). The XRD patterns of the Bangkok clay indicate the presence of mainly quartz, with some kaolinite, montmorillonite, and illite in the Bangkok clay. Then, the main component of the BA was quartz, while the OPC showed the

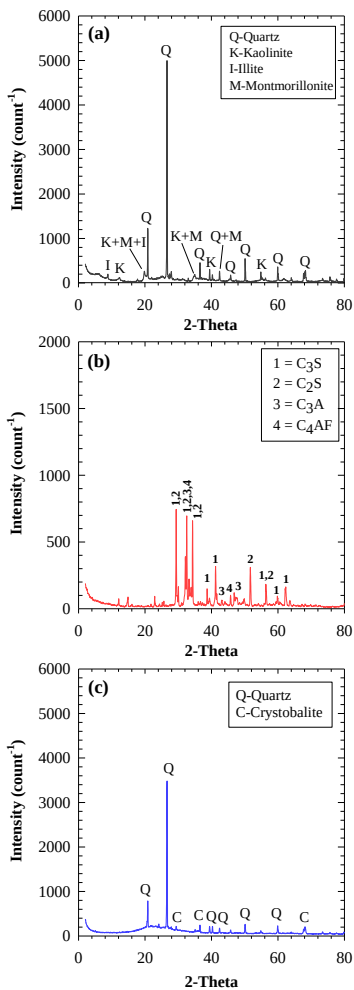


Figure 1. XRD analysis of: (a) soft clay, (b) OPC, and (c) BA samples

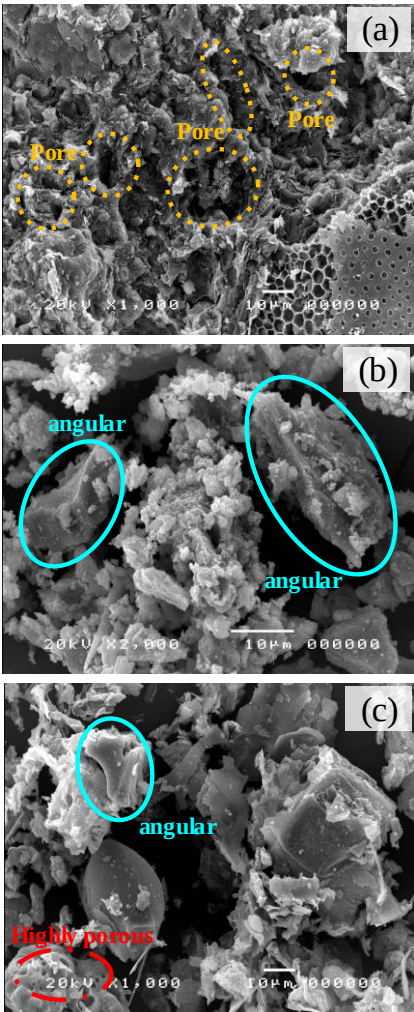


Figure 2. SEM images of: (a) soft clay, (b) OPC, and (c) BA samples

4 main cement minerals: C_3S , C_2S , C_3A , and C_4AF . The surface characteristics of the materials were examined using SEM. The images obtained at approximately 1,000 magnification are provided in Figure 2. The soft clay image shows its groups and clusters (Figure 2(a)). The OPC particles are angular in shape (Figure 2(b)), and the BA particles are angular in shape with rough surfaces and highly porous textures (Figure 2(c)).

The grain size distribution of the soft clay was obtained using a hydrometer. The grain size distribution of the OPC and BA were obtained via a laser diffraction particle size analyzer determining the particle size distribution and mean particle size. Figure 3 shows the particle size distribution of the soft clay, OPC, and BA. The average particle sizes of the OPC and BA were similar, and the average particle size of the soft clay was approximately 3 times smaller than the average particle sizes of the OPC and BA.

Method

A series of laboratory tests consisting of unconfined compressive strength (UCS) tests were conducted by varying the OPC doses and BA contents. The amount of OPC in current practice ranges from 80 to 200 kg/m^3 for improvement of soft Bangkok clay (Department of Highways and Japan International Cooperation Agency, 1998). Thus, this study used an OPC content of 200 kg/m^3 of soil and a W/B ratio

of 0.8, 0.9, 1.2, and 1.5. In this study, some additional mixtures were prepared with cement alone for comparative purposes. In the OPC-BA combinations, the BA was used as 10%, 20%, 30%, and 40% of the cement substitution in the selected binder dosages. In this regard, a total of 4 samples were prepared in the following OPC-to-BA proportions: 90:10, 80:20, 70:30, and 60:40 (CBA10, CBA20, CBA30, and CBA40, respectively). The soil-cement admixture was prepared according to the Japanese Geotechnical Society standard JGS T821-1990 (Japanese Geotechnical Society, 1990) by using the kneading technique. Cylindrical specimens that were 50 mm in diameter and 100 mm in height were prepared for the UCS tests. After 24 h of curing in the mold, specimens were moved and rapidly wrapped with a plastic sheet to prevent moisture loss. The UCS tests were conducted after curing the samples for 3, 7, 28, 60, and 90 days. After the UCS tests, some block-shaped samples were collected to further investigate the changes in the microstructure of the stabilized soft clay. The block samples were approximately 3 to 7 mm long and were removed from the failure plane of the sample and placed in a container with desiccant to dry.

Results and discussion

Unconfined Compressive Strength Versus Curing Time

When the OPC and BA are blended with soft clay in the presence of water, a set of reactions occurs that results in the dissociation of the CaO in the cement and BA and the formation of cementitious and pozzolanic gels (calcium silicate hydrate gel, (CSH)). First, the OPC hydration reaction occurs. The pozzolanic reaction is a secondary reaction that immediately follows the hydration of the OPC. SiO_2 from the BA gradually sequesters the calcium hydroxide, Ca(OH)_2 , remaining after the CSH formation. When the Ca(OH)_2 is consumed to a lesser concentration, the pozzolanic reaction no longer occurs. The left over BA powder does not contribute any cementing property to the matrix. (Jamsawang *et al.* 2017).

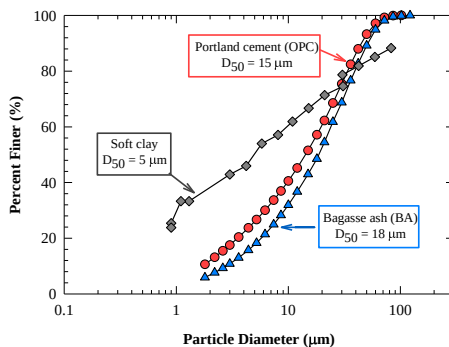


Figure 3. Particle size distribution curves of unstabilized soft clay, OPC, and BA

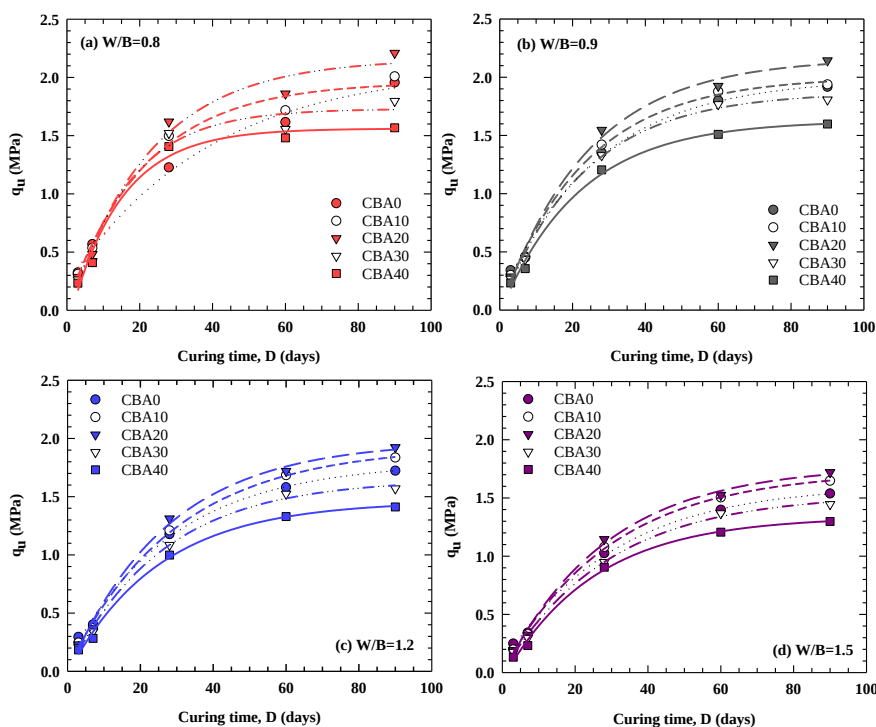


Figure 4. Strength development with time in the BA-blended OPC admixed with soft clay

Figure 4(a-d) shows the effects of the curing time and stabilizer content on the strength of the OPC-BA stabilized soft clay for the of 0.8, 0.9, 1.2, and 1.5 W/B ratio samples, respectively. Noticeably, the strength increases steadily as the curing time increases; thus, the strength development with the curing time can be represented using an exponential function, because the short-term strength of about 7 days of curing is generally used for design. During the early stage at 3 and 7 days, the q_u decreases as the amount of the BA increases. The strength values of the mixes containing the BA were lower than those of the control CBA0 (only OPC content). At 28 days, CBA10 and CBA20 had higher strengths than CBA0 and the other mixtures. At 60 and 90 days of curing, CBA20 had the highest compressive strength and CBA40 had the lowest compressive strength. In addition, CBA40 had the lowest strength following all the curing periods. When considering the W/B ratio on the

strength, the W/B ratio of 0.8 provided the highest strength for all curing times and all the W/B ratios.

From the laboratory test results, various parameters were found to affect the q_u value of the OPC-BA stabilized soft clay, the curing time (D), the BA replacement content (%BA), and the W/B ratio. All these influence parameters have nonlinear relationships with the q_u value of the OPC-BA stabilized soft clay. To combine the influence parameters, multiple regression analysis was performed. The resulting regression for the OPC-BA stabilized soft clay with the replacement of BA at 0–40% is as follows:

$$q_u = 0.636 + 0.0368\left(\frac{D}{2.5^{W/B}}\right) - 0.0496\left(\frac{\%BA}{D}\right), R^2 = 0.8560 \quad (1)$$

Comparisons between the experimental data and the values predicted using Equation (1) are presented in Figure 5. The measured q_u

was 1 times the predicted q_u , with $R^2 = 0.8560$. It can be seen that the predicted strengths satisfactorily agree with the experimental results.

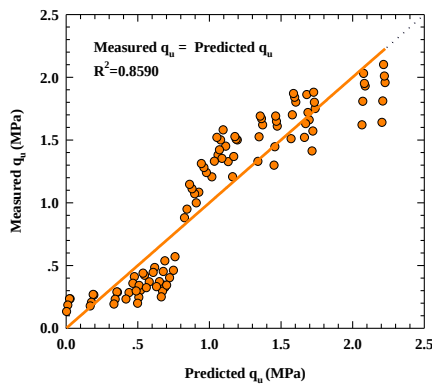


Figure 5. Predicted versus measured unconfined compressive strength

Optimum BA Replacement Content

Figure 6 presents the relationship between the BA replacement level and the compressive strength for all the W/B ratios and curing times. The results indicate that 20% of BA seems to be the optimum limit. As mentioned in the previous section, CBA20 provides the highest compressive strength for all curing times and CBA40 had the lowest strength in all cases. The high content of the OPC combined with 20% of the BA induces more hydration reaction than that combined. It is certain that the incorporation of the BA stabilizes soft clay due to its fine particle size, high surface area, high silica content, the high degree of reactivity of BA, and the high pozzolanic reaction between calcium hydroxide and reactive silica in (Akram *et al.* 2009). Normally, BA can be considered as a pozzolanic material and its small particles fill the voids in the concrete structure, which increases the compressive strength of the concrete (Rukzon and Chindaprasirt, 2012). From the test results mentioned above, it is suggested

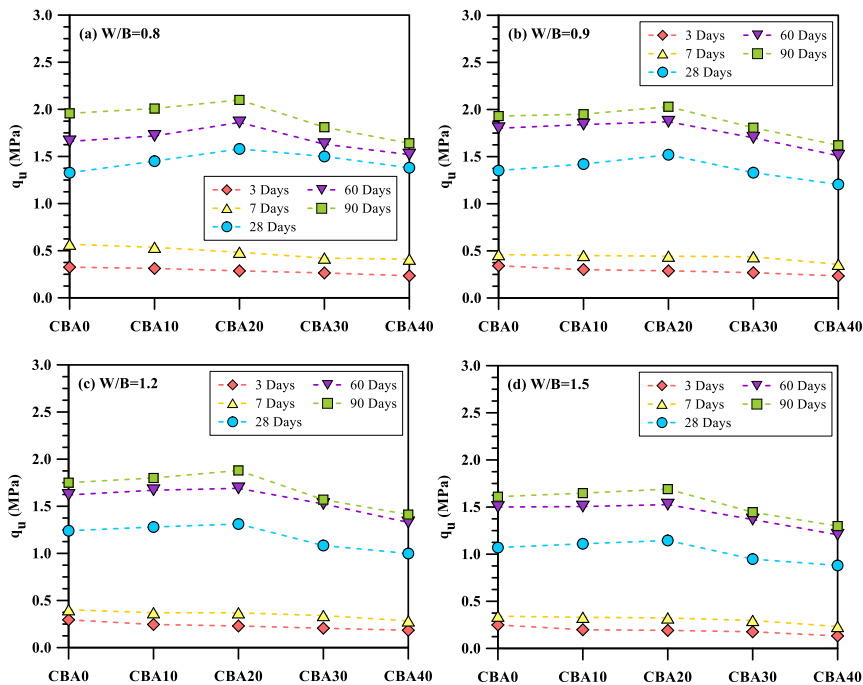


Figure 6. Relationship between BA replacement level and compressive strength

that the BA being effective for stabilizing soft clay soils in this study is consistent with what was reported by Dang *et al.* (2015) who used BA and hydrated lime to stabilize expansive soil.

Modulus of Elasticity

The relationships of the elastic modulus and strength of the of 0.8, 0.9, 1.2, and 1.5 W/B ratio samples are shown in Figure 7. Referring to the current application, the design method of a cement column which serves as the bearing resistance uses 50% of its strength. The E_{50} can be approximately estimated as $40.91q_u$ and $R^2 = 0.9155$. Therefore, a quantitative correlation potentially exists between q_u and E_{50} . In terms of this relationship, many authors have reached valuable conclusions (Jamsawang *et al.* 2016). The correlation between E_{50} and q_u is generally linear and is within the wide range of results obtained in previous studies. However, in this study it is different from the linear relationships observed in previous studies due to differences in the soil properties (such as the soil heavy metal and organic matter contents) and the use of stabilizers with different components (such as cement, bagasse ash, the W/B and their amounts).

Microstructure of the OPC-BA Stabilized Soft Clay

This study focuses on understanding the changes in the microstructures of the OPC-BA

stabilized soft clay. Figure 8 shows the changes in the microstructures of samples CBA0, CBA20, and CBA40 (Figure 8(a-c), respectively) after 28 days of curing. The SEM image of CBA0 is similar to that of CBA20. Many hydration products can be observed, the surfaces of the samples were rough, and the products contained CSH gel and ettringite crystals. The cementitious compounds (as pozzolanic reaction products) fill the pore spaces. Consequently, the strength of the OPC-BA stabilized soft clay significantly increases as the BA content

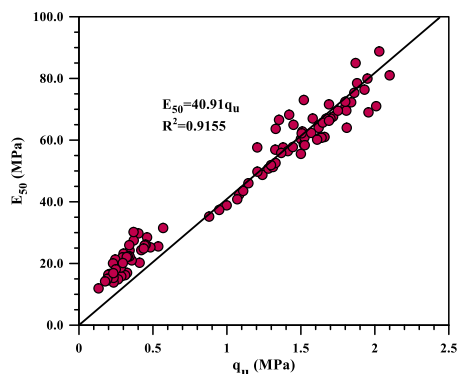


Figure 7. Relationship between modulus of elasticity E_{50} and q_u

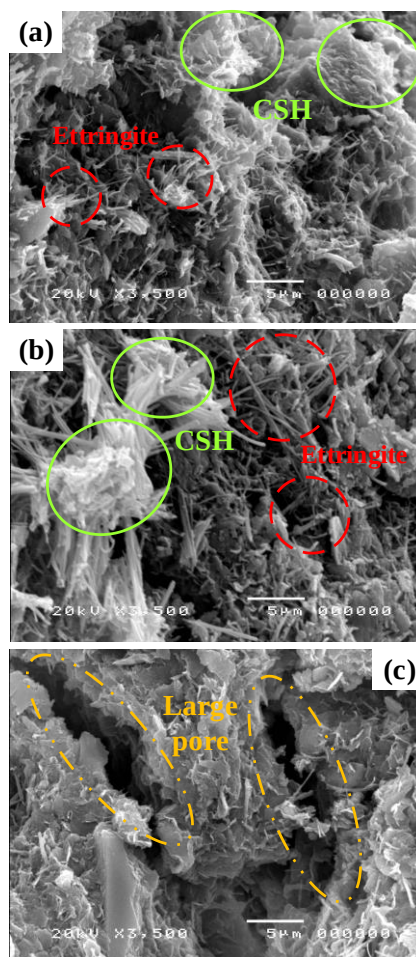


Figure 8. SEM images of the samples after 28 days of curing: (a) CBA0, (b) CBA20, and (c) CBA40 at a magnification 3,500

increases, as described above. The SEM image of CBA40 (Figure 8(c)) shows that it is highly porous, with the pore spaces being relatively larger than those observed in CBA0 and CBA20.

Conclusions

Based on the experimental results, the conclusions can be drawn as follows:

- BA can slightly improve the compressive strength of soft clay. Additionally, the effect of the W/B ratio on the compressive strength of soft clay does not significantly affect the normalized strength because the ratio of strength varies in a narrow range.

- The curves of strength development versus time for the OPC-BA-stabilized and cement-stabilized soft clays were similar for the of 0.8, 0.9, 1.2, and 1.5 W/B ratio samples because the same hydration and pozzolanic reactions occurred. The W/B ratio of 0.8 provided the highest strength for all curing times and all the W/B ratios. The use of 10-20% BA can enhance the value of q_u by as much as approximately 1.045-1.073 times that of OPC alone, whereas the use of 30 and 40% BA results in approximately 0.925-0.838 times lower strength than that of OPC alone. The correlation between E_{50} and q_u is linear ($E_{50} = 41.91q_u$).

- The replacement of 20% of the OPC with BA was optimal for improving the strength of the soft clay because it provided the highest strength and appropriate proportions of SiO_2 (from the BA) and $Ca(OH)_2$ that were sufficient for the pozzolanic reactions that resulted in the formation of the CSH. When 40% of the OPC was replaced by BA, the lowest strength was observed because the amount of $Ca(OH)_2$ resulting from the pozzolanic reactions was not sufficient to improve the soil strength.

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